A SYSTEM FOR ON-LINE COMPUTER ANALYSIS OF DATA DURING HEART CATHETERIZATION

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The use of computers for collection, analysis, and display of physiological data in real-time presents an interesting dilemma. On the one hand, the computer system must be available when the physiological event is taking place but, on the other hand, the sampling rates required to describe cardiovascular physiological events (from 4 to 200 samples/second/channel) do not utilize the full capability of most present-day computing systems. For this reason, a time-sharing system (MEDLAB) (2) has been developed for the Control Data 3200 computer which permits sharing of the computer among 14 remote stations located in four hospitals (1). These stations include animal research laboratories, cardiovascular diagnostic facilities, intensive care monitoring wards, pulmonary function laboratories, portable stations for use in individual patient rooms, and others.

Figure 206 shows a remote terminal built around a Tektronix 564 memory oscilloscope which serves as an X-Y plotter to display graphical and alphanumeric information. Characters and graphs generated by the computer are sent through digital-to-analog converters which drive the X, Y, and Z axes of the memory oscilloscope. Control of computer programs is accomplished by using the 12-key decimal keyboard or the CALL or OCTAL buttons. These buttons interrupt the computer and cause it to read a 12-bit binary code from a four-digit octal switch. The eight small indicator lamps indicate to the operator at the remote station the status of the computer and of his own program.

During a heart catheterization, the physician uses a sterile plastic wand to depress the buttons and dial option codes on the four-digit octal switch. The highest-order digit of this switch indicates the type of data to be processed, such as pressure, oxygen saturation, dye dilution, or pressure gradient. The next digit is used to indicate the state of the patient; for instance, zero means 'at rest breathing room air'. The two lower-order digits indicate the anatomical position of the catheter in the cardiovascular system and are ar-

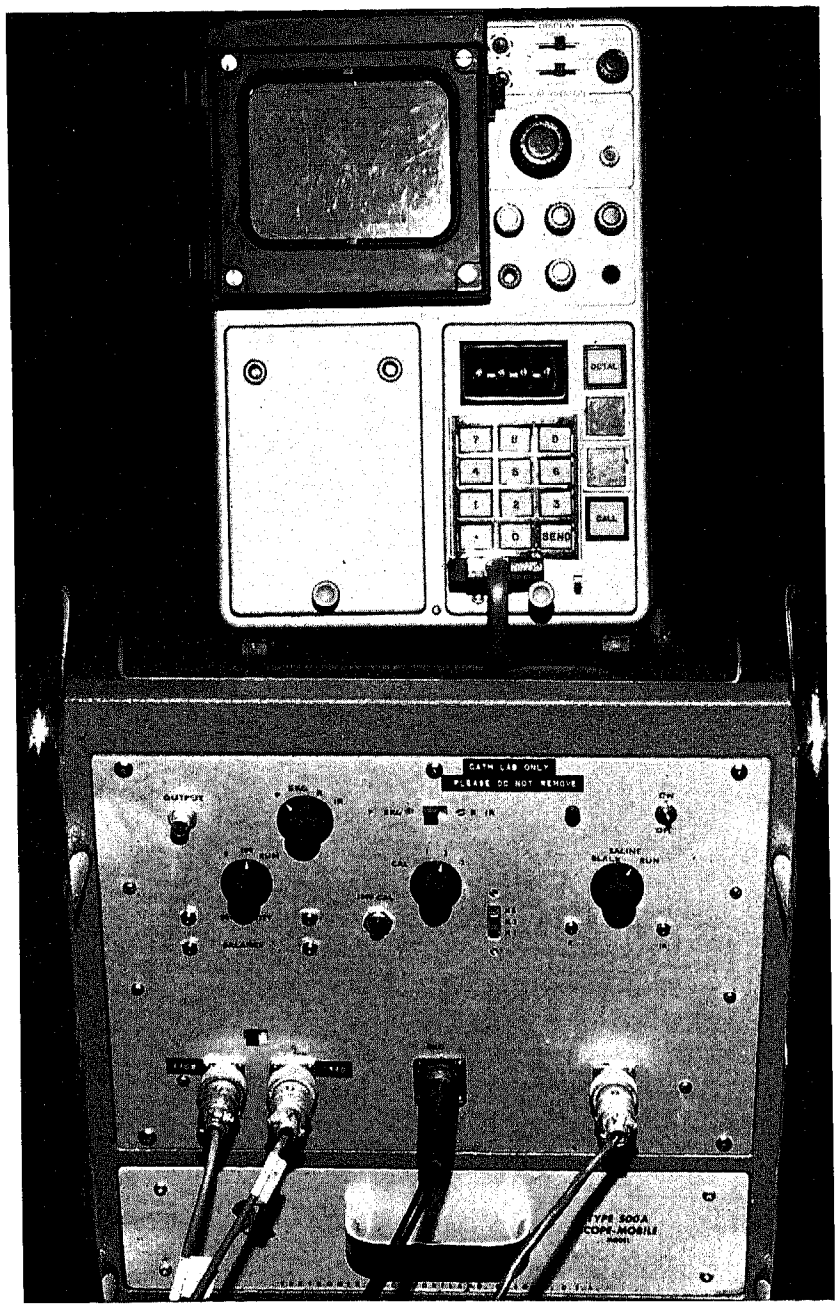

Figure 206. Remote computer terminal. See text.

ranged from zero through 25 following the anatomical structures of the blood flow, from the venous to and through the arterial system. After the physician has selected his option code he depresses the octal button, which causes the computer to interrupt and read the number contained in the octal switch. The computer acknowledges the code by writing back the interpretation of each digit on the scope, thereby giving the operator a chance to confirm or deny the code before proceeding to input data.

Below the scope in the mobile cart is an instrumentation package designed especially to preprocess signals encountered in a cardiovascular laboratory. Built around small solid-state plug-in operational amplifiers, this unit preconditions all signals to levels, amplitudes, and frequencies acceptable to the analog-to-digital converter. On the left is a two-channel pressure gauge amplifier, in the center is an ECG amplifier, and the module on the right amplifies signals from the red and infrared cells of a Wood oximeter. Front panel screwdriver controls are used to initially balance and adjust sensitivities; when once set for a particular transducer, these need not be adjusted again from day to day.

Programs that have found general usage in all of the cardiac catheterization laboratories, as well as in the experimental laboratories, will be described below. It should be pointed out, however, that these are not all the programs available and, in fact, several special programs have been developed for use in one or another cardiovascular laboratory to satisfy the requirements of a particular physician. Data generated by these programs are stored on magnetic discs, along with the time and date that the measurement was performed. Therefore, as will be evident, there is no need for strip chart recording of the records or for keeping a running log of the events during the catheterization or during a physiologic experiment.

Oxygen Saturation

The voltages from the red and infrared cells of a Wood oximeter are scaled and biased through operational amplifiers so that black level is near one extreme of the range of the analog-to-digital converter, and the output (with saline in the cuvette) is near the other extreme with the sensitivity set at one-half normal. This arrangement guarantees that the output of both cells will be within range of the analog-to-digital converter, even with large variations of hematocrit, with blood flowing through the cuvette and with the amplifier set at normal sensitivity. The signals are filtered by a simple low-pass filter (1Hz-3db) before being sampled by the analog-to-digital converter. The computer samples the red and infrared signals four times per second after the operator presses his SEND button, until eight successive samples are within one bit of each other (one part in 256). If this fails to occur within five seconds, the message UNSTABLE READING is returned to the operator.

Figure 207 is a photograph of the face of a storage oscilloscope showing

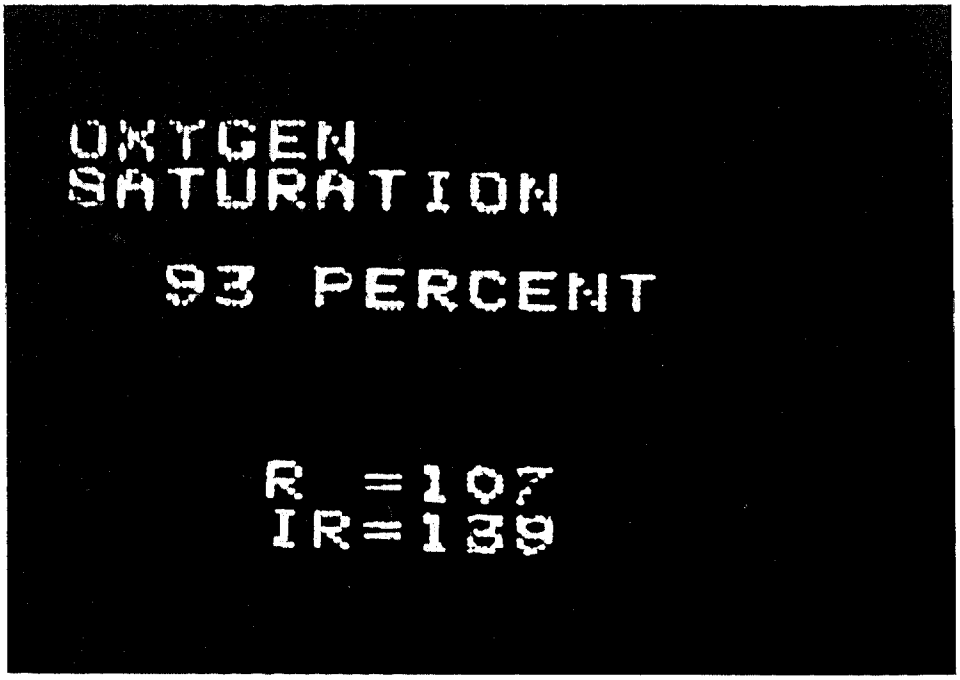

Figure 207. Remote terminal display of oxygen saturation in the radial artery.

an oxygen saturation reading of 93 per cent, taken from the radial artery. This result is available and displayed back to the operator within one second after the reading is taken. The R and IR readings at the bottom of the figure are used as a check of the electrical response of the system. Percentage saturation readings are consistent from day to day (± 3 per cent) and use the same calibration until lamps or cuvette chambers are changed. Logarithmic conversion is made by the computer, thus greatly simplifying the input electronics. Calibration is accomplished at 100 and 70 per cent saturation by sampling arterial blood from a normal subject breathing 100 per cent oxygen, and mixed venous blood with the same subject breathing room air. To improve the sensitivity of this system, a 10-bit analog-to-digital converter is being installed to replace the present 8-bit unit.

Pressure Analysis

Figure 208 shows a display resulting from the pressure analysis program. These results were obtained by sampling the radial artery pressure and electrocardiogram at 200 samples per second. Using the QRS complex as a trigger, pressure waveforms from six successive heart cycles were sampled and averaged. The curve at the bottom is the averaged waveform, with minimum and maximum points marked by vertical lines. Systolic, diastolic, and mean pressures are 97, 64, and 77 mm Hg, respectively. The variance

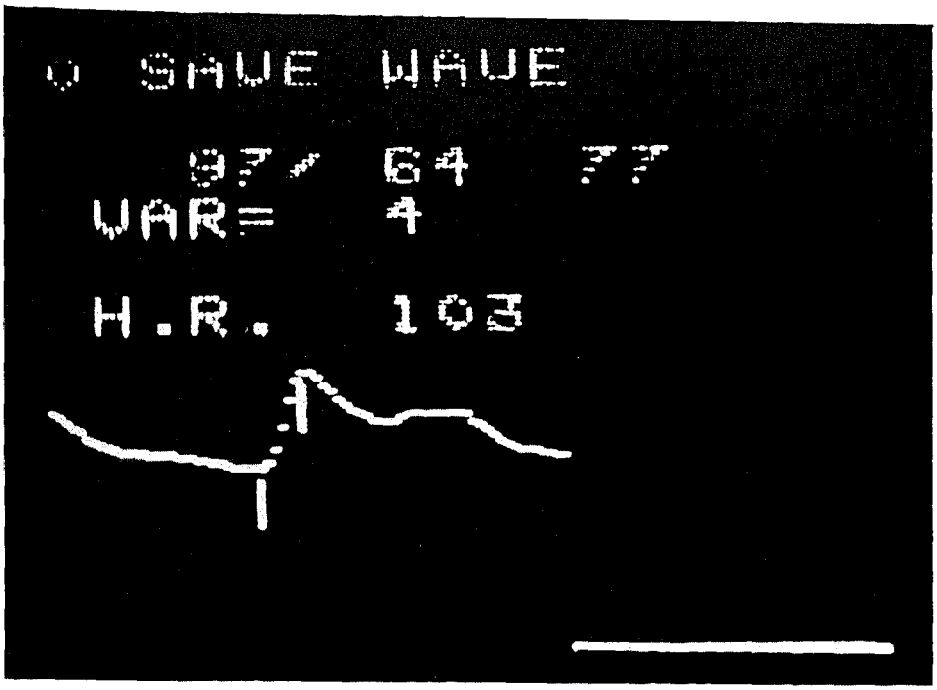

Figure 208. Radial artery pressure analysis results as displayed on terminal. See text.

around this averaged waveform was four, and heart rate was 103 per minute. In the case of ventricular pressures, the program detects peak systolic, beginning diastolic, and end-diastolic pressure. For atrial pressures or pulmonary artery "wedge" pressure, peak "A" wave, peak "V" wave, and mean pressure are measured. The pressure waveform can be saved and plotted as part of the final report, along with the print-out of the numerical data. Also, this waveform may be used for pressure gradient analysis, as will be described later.

The instrumentation package has been set up so that 0 to 200 mm Hg corresponds to full scale on the analog-to-digital converter. Therefore, since the converter is an eight-bit machine, resolution of the pressure system is approximately 1 mm Hg. Stability of the D.C. amplifier and regulated D.C. supply used to excite the strain gauge limits drift to less than 1 mm Hg during a catheterization procedure. At the beginning of each catheterization, pressure calibration is entered once, using a mercury manometer.

Dye Dilution Curve Analysis

Figure 209 shows data presented by the computer on completion of a dye dilution curve for cardiac output determination. The infrared cell of the Wood cuvette oximeter is used to detect concentration of indocyanine green* dye in circulating blood. The output of this cell is calibrated by first

* Cardio-Green (CG); Hynson, Westcott & Dunning, Inc., Baltimore, Maryland.

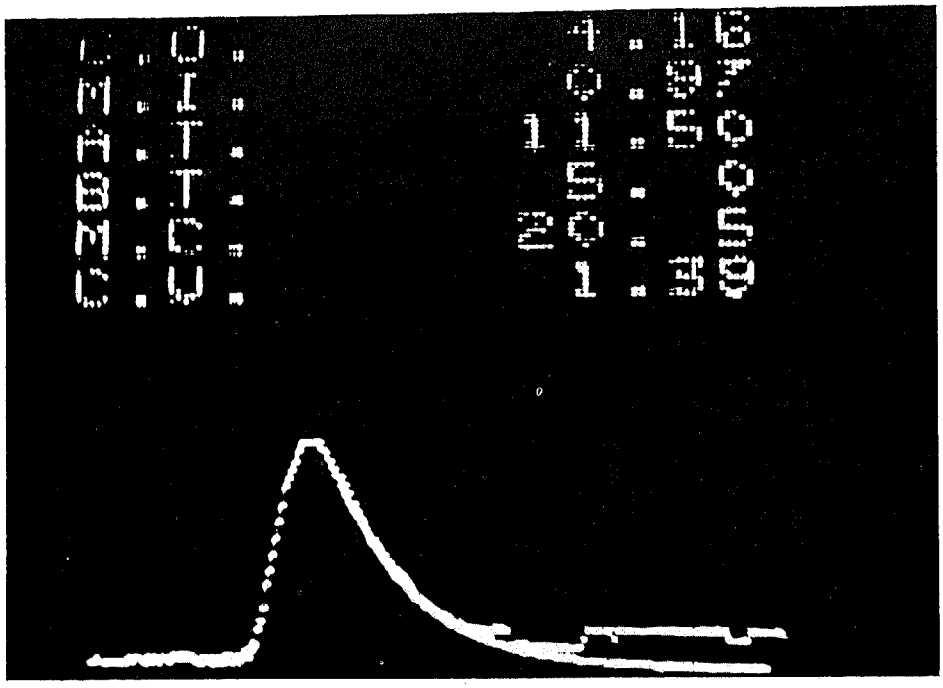

Figure 209. Plot of dye dilution curve and extrapolation from results determined by cardiac output test. *C.O.:* Cardiac output; *M.I.:* mitral insufficiency; *A.T.:* appearance time; *B.T.:* build-up time; *M.C.:* mean circulation time; *C.V.:* central blood volume.

entering black and saline levels as for oximetry. Then, 19 cc of nondyed blood is withdrawn from the patient through the cuvette to give a "zero" dye indication. This 19 cc sample is mixed with 1 cc of saline containing 0.25 mg of dye, and then reinfused through the cuvette as the computer enters another reading corresponding to 12.5 mg/liter concentration of dye. The dye analysis program is then recalled, and this time the operator is requested to enter the sampling time in seconds. Then, with blood flowing through the cuvette, dye is injected as a keyboard button is pressed, indicating the number of cubic centimeters of dye injected. This causes the computer to start sampling the infrared cell output at four samples per second, and to perform the necessary logarithmic conversions. Data from the first two seconds are averaged and used to represent zero dye concentration and to establish the system noise level. The time-course of dye concentration is plotted point-by-point as mg/liter on the scope as it is being generated. At the end of the specified sampling period, if dye concentration following this initial hump has not returned to within the noise level of the baseline, the descending slope is analyzed to find which two-second segment most closely fits an exponential, with the constraint that the extrapolation must not exceed the measured dye concentration at any point by more than the noise

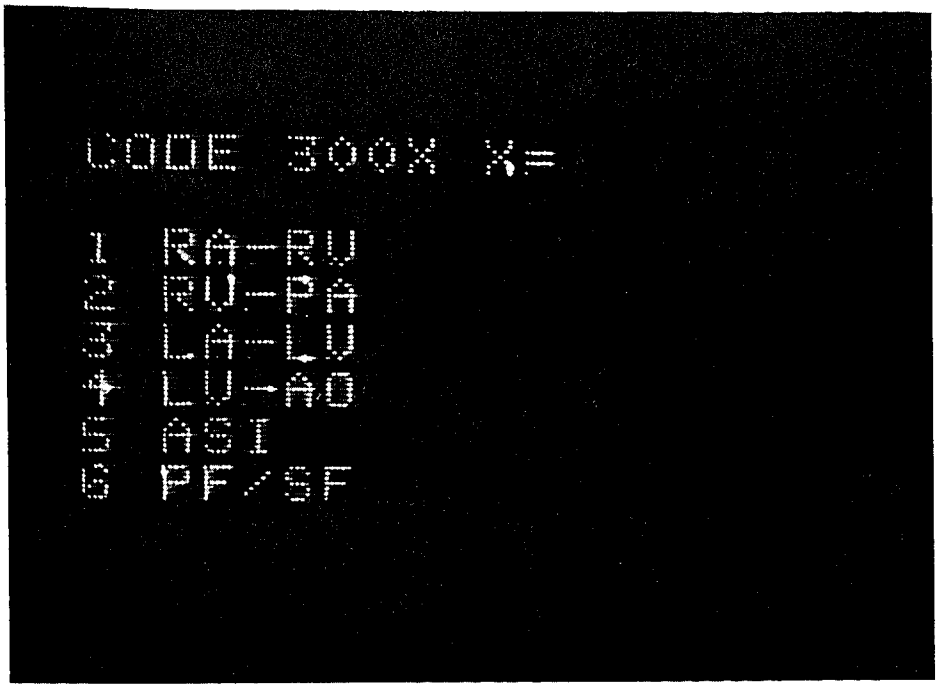

Figure 210. Options for the pressure gradient analysis program *1:* Pressure gradient between right atrium (RA) and right ventricle (RV); *2:* between RV and pulmonary artery (PA); *3:* between left atrium (LA) and left ventricle (LV); *4:* between LV and aorta (AO); *5:* index of aortic stenosis (ASI); *6:* ratio of pulmonary-to-systemic blood flow (PF/SF) in patients with left-to-right shunts. If option *4* were chosen, the results shown in Figure 211 would appear.

level of the signal. The extrapolated curve is then plotted over the experimental curve for comparison.

For the curve shown in Figure 209, the calculated values were the following: cardiac output, 4.16 liters/min.; mitral insufficiency index (a measure of skewness of the curve), 0.97; appearance time, 11.50 sec.; build-up time, 5.00 sec.; mean circulation time, 20.5 sec.; and a central blood volume of 1.39 liters. The curve itself is stored on a magnetic disc for later plotting on the report and for shunt analysis if the curve is abnormal.

Pressure Gradient

Figure 210 shows the options for the pressure gradient analysis program. This program can be used to measure pressure gradients across any of the valves, for calculating an index of aortic stenosis from the rate of rise of aortic pressure, or for calculation of the ratio of pulmonary-to-systemic blood flow in patients with left-to-right shunts. Were option #4 chosen, the results shown in Figure 211 would appear. Here the measured mean systolic pressure gradient between left ventricle and aorta for this patient with aortic

Figure 211. Results of a pressure gradient analysis between left ventricle (LV) and aorta (AO). MEAN GRAD: Mean systolic pressure gradient.

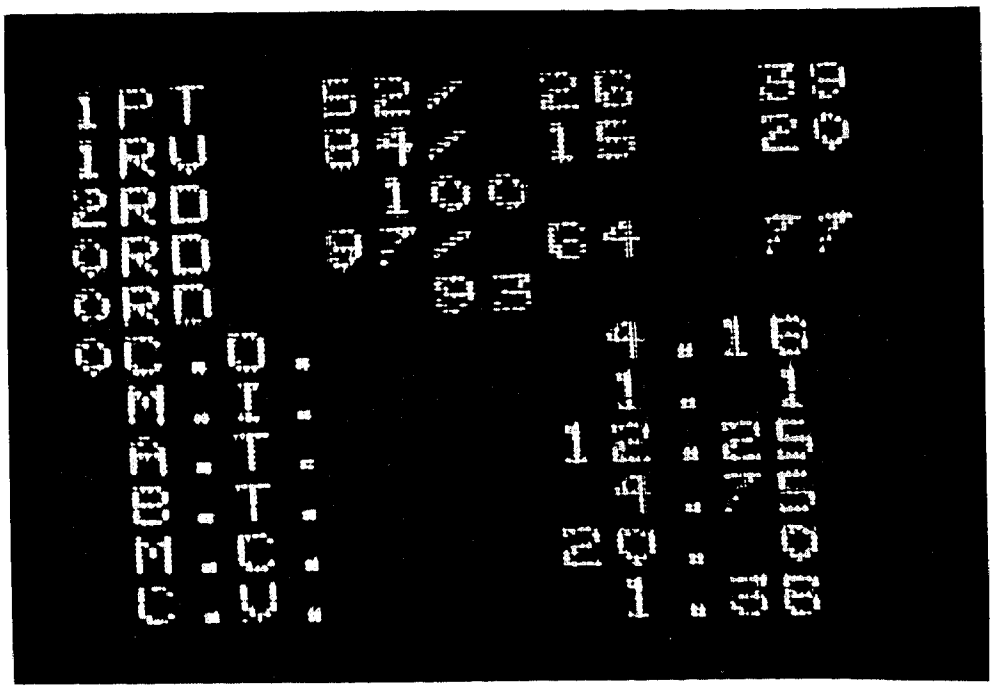

Figure 212. Data display at remote station illustrating review and edit capability. Note display of pressure values obtained during the cardiac catheterization procedure (Figure 213). The lower portion of the display contains data from dye curve No. 1. See text.

LDS HOSPITAL CARDIOVASCULAR LABORATORY CATHETERIZATION REPORT

FRED PASSARELLA R12-11-67 LDSH LAB NO. 1283 AGE 52 SEX M DR. W. R. RUKEL

TIME	LOCATION	SATURATION	MMHG	HR	BREATHING	STATE	COMMENT
10 44	SUP VC	71 %			AIR	REST	
10 44	MID R A	69 %			AIR	REST	
10 45	MID R V	64 %			AIR	REST	
10 46	MID R V		71/ 2- 8	113	AIR	REST	
10 48	MID R A		12- 9 (5)	107	AIR	REST	
10 49	PA TRNK	62			AIR	REST	
10 49	PA TRNK		28/ 11 (19)	105	AIR	REST	
10 50	MID R V		68/ 3- 7	111	AIR	REST	
10 54	PA WEDGE		25-18 (16)	111	AIR	REST	
10 55	PA WEDGE	100 %			AIR	REST	
11 5	PA WEDGE		37-31 (26)	107	AIR	EXERCISE	
11 5	PA WEDGE	101 %			AIR	EXERCISE	
11 12	PA TRNK		52/ 26 (39)	107	AIR	EXERCISE	
11 13	MID R V		84/ 15-20	125	AIR	EXERCISE	
11 20	RAD ART	100 %			OXYGEN	REST	
11 26	RAD ART		97/ 64 (77)	103	AIR	REST	
11 30	RAD ART	93 %			AIR	REST	

11 37 PA TRNK AIR REST CURVE 1

CARDIAC OUTPUT	4.2	L/MIN
CARDIAC INDEX	2.8	L/MIN(M)2
MITRAL INDEX	1.01	
APPEARANCE TIME	12.3	SEC
BUILD UP TIME	4.8	SEC
MEAN CIRC. TIME	20.0	SEC
CENTRAL BLOOD VOL	1.4	LITERS

11 45 PA TRNK AIR REST CURVE 2

CARDIAC OUTPUT	4.0	L/MIN
CARDIAC INDEX	2.7	L/MIN(M)2
MITRAL INDEX	0.90	
APPEARANCE TIME	12.3	SEC
BUILD UP TIME	4.3	SEC
MEAN CIRC. TIME	19.7	SEC
CENTRAL BLOOD VOL	1.3	LITERS

11 45 PA TRNK AIR EXERCISE CURVE 3

CARDIAC OUTPUT	3.8	L/MIN
CARDIAC INDEX	2.5	L/MIN(M)2
MITRAL INDEX	0.75	
APPEARANCE TIME	14.8	SEC
BUILD UP TIME	5.5	SEC
MEAN CIRC. TIME	24.1	SEC
CENTRAL BLOOD VOL	1.5	LITERS

12 26	MID L V		197/ 11-11	111	AIR	REST
12 28	PA WEDGE		22-12 (11)	111	AIR	REST
	LALV(DY)	MEAN GRADIENT=	4			
12 30	MID L V		196/ 14-14	113	AIR	REST
12 32	HIGH L V		87/ 16-23	117	AIR	REST
12 36	ASC AORT		93/ 64 (78)	115	AIR	REST
	MARV(DY)	MEAN GRADIENT=	3			
	RVPA(SY)	MEAN GRADIENT=	26			
	MRVPA-SY	PEAK GRADIENT=	40			
	LALV(DY)	MEAN GRADIENT=	4			
	LVAO(SY)	MEAN GRADIENT=	62			
		AORTIC STENOSIS INDEX	16			

L.V. ENTERED VIA AORTIC VALVE

ABNORMAL FINDINGS

PULMONARY STENOSIS,INFUNDIBULAR
PULMONARY STENOSIS,VALVULAR
AORTIC STENOSIS,SEVERE

Figure 213. Computer print-out of final results of the heart catheterization study.

stenosis is 62 mm Hg, and the waveforms are displayed superimposed as they will appear in the final printed report.

Editing

One of the most important advantages of on-line processing of data during a diagnostic cardiac catheterization is the ability to review results while the procedure is still in progress. This procedure makes it possible to repeat measurements of borderline significance or of questionable validity while the catheter is still in place. Figure 212 shows one page of data displayed at a remote station for review and editing. At the top is a pressure reading taken in the pulmonary artery trunk with the patient breathing room air and exercising, showing peak systolic, beginning diastolic, and mean pressures. Next is the pressure in the right atrium—"A" wave, "V" wave, and mean. On

pressing the INTERRUPT button, the reviewer may look at additional data, eliminate unwanted data, or scale all oxygen saturation readings up or down by a fixed amount. On request he may call for a print-out of any number of copies of the edited report, including a summary of all abnormal findings and diagnosis of the physiologic defects, as shown in Figure 213. At the time of print-out, the data are copied from disc to a master data tape, where they are saved for later statistical processing.

Comment

This system has been in operation for a total of three years and has been used as a routine clinical tool for more than two years, with the data obtained and printed out by the computer being sent to the attending physician as a final report of a cardiac catheterization. Instigation of this procedure allowed reduction in the number of technicians helping the physician from two to one in a routine catheterization, permitted the physician to perform two catheterizations per day, and eliminated the tedious job of data reduction from a graphical recording of pressures and dye curves. Also, the computer is an unbiased observer and gives quantitative results, eliminating the somewhat subjective reading and choosing of representative pressure waveforms from graphical recordings, as is commonly done with manual methods. At present we have over 450 cases stored on magnetic tape which are forming a data base for later statistical processing.

REFERENCES

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2. PRYOR, T. A., and WARNER, H. R., Time-sharing in biomedical research. *Datamation*, 1966, **12**: 54-63.